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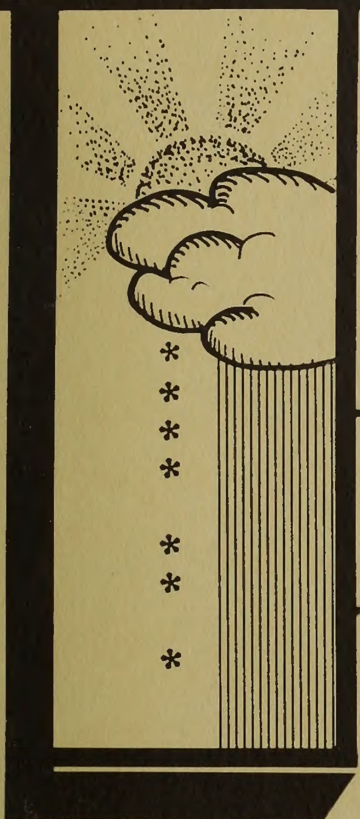

CLIMATOLOGY

Climatological Analysis for Mined-Land Reclamation

U.S. DEPARTMENT OF THE INTERIOR
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Climate is an important environmental factor. It places limitations on reclamation activities. It also influences the probability of successful reclamation of mined lands. Climate has usually been included in reclamation plans in a broad way; this report presents a method for making better use of climate information. It includes steps such as identifying reclamation activities and analyzing and interpreting appropriate climatic information.

"Climate Profiles for Reclamation" have been developed which bring together reclamation activities, vegetation considerations, problems, opportunities, and climatic analyses. Hydrologic, biologic, and ecologic processes and related climatic elements which influence mining are also discussed. General information about data sources and characteristics of climate variations are presented. Climate profiles are developed, examples are shown, and their interpretation and use are explained. Recommendations for using climatic information are also enumerated at the end of this report.

This report only addresses the climatic aspects pertinent to revegetation. Many other processes and expertise from other fields need to be brought together before a total reclamation program can be planned and carried out.

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CLIMATOLOGICAL ANALYSIS

FOR

MINED-LAND RECLAMATION

by
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The Bureau of Land Management has played an important role in the interagency Federal Coal Management Program by being responsible for leasing Federally owned coal. A large part of BLM's effort has been to determine postmine land use and to assure that leased land is in suitable condition to support that use after being mined. A series of technical investigations was initiated to help make the required determinations.

Climatology and Mined-Land Reclamation is part of a report series resulting from these technical investigations.* It describes the effects of the climate resource on reclamation practices. It also makes recommendations, based on climatic limitations, which will promote the successful return of mined land to its predetermined postmine land use.

Limited copies of this report are available from:

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*This BLM Technical Report was originally published by the Colorado Climate Center at Colorado State University under the title Development of Climate Profiles for Reclamation.

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ABSTRACT

Climate is an important environmental factor. It places limitations on reclamation activities. It also influences the probability of successful reclamation of mined lands. Climate has usually been included in reclamation plans in a broad way; this report presents a method for making better use of climate information. It includes steps such as identifying reclamation activities and analyzing and interpreting appropriate climatic information.

Climate Profiles for Reclamation have been developed which bring together reclamation activities, vegetation considerations, problems, opportunities, and climatic analyses. Hydrologic, biologic, and ecologic processes and related climatic elements which influence mining are also discussed. General information about data sources and characteristics of climate variations are presented. Climate profiles are developed, examples are shown, and their interpretation and use are explained. Recommendations for using climatic information are also enumerated at the end of this report.

This report only addresses the climatic aspects pertinent to revegetation. Many other processes and expertise from other fields need to be brought together before a total reclamation program can be planned and carried out.

RECOMMENDATIONS

This study resulted in the following recommendations:

-- Reclamation problems (and opportunities) vary with climate and geographic locations.

-- Solutions to reclamation problems are usually interdisciplinary.

-- Analyses must be performed in developing the climate profile which addresses problems and opportunities most likely to be encountered at the particular site.

-- Probable magnitude of spatial variations of climate must be determined for any area of interest prior to obtaining data and beginning the climate profile.

-- A trained climatologist is needed to prepare and interpret climatic analyses in areas with large spatial variations in climate.

-- Sufficient data must exist to perform climatic analyses. (The number of years of existing data must be enough to determine averages, variations, and extremes with adequate precision.)

-- Data quality and representativeness must be questioned.

-- More research is needed to:

    -- Relate reclamation vegetation and climate.
    -- Learn how to interpolate climatic data in complex terrain.

INTRODUCTION

Climate is an important environmental factor which places inherent limitations on reclamation activities and influences the probability of successful reclamation of mined lands. Despite its importance, climate has generally been incorporated into mining and reclamation plans only in a broad and qualitative way. This report presents a methodology for making better use of climate information. By carefully identifying reclamation activities and their responsiveness to climate, followed by analyses and interpretation of appropriate climatic information, reclamation procedures, planning, and decisionmaking can and should be adjusted and improved.

The methodology described in this report leads to the development of what will be called "Climate Profiles for Reclamation." In these profiles, reclamation activities, vegetation considerations, problems, opportunities, and climatic analyses are brought together. This structure helps point out the intrinsic interrelationships between climate and reclamation, which shows the value and benefit of wise use of climate information.

In the sections that follow, several topics pertinent to the development of climate profiles for reclamation are discussed and surface mining and reclamation activities are listed. Hydrologic, biologic, and ecologic processes and the related climatic elements influencing or influenced by mining and reclamation are then briefly described. General information about data sources and characteristics of climate variations are presented. Finally, climate profiles are developed, examples are shown, and their interpretation and use are explained.

Although climate plays a dominant role in successful revegetation, hydrologic processes and physical and chemical soil properties sometimes exercise overriding deterrents to successfully reestablishing plants. This report addresses only the climatic aspects pertinent to revegetation. Many other processes and expertise from many other fields must be brought together before a total reclamation program can be planned and carried out.

Hydrologic, biologic, and ecologic processes are intimately interrelated. Collectively, these interrelated processes form an ecosystem which is characterized by particular plants, animals, and microorganisms. Such an ecosystem is limited and bounded by characteristics of the local climate and also by the nature of the soils. These natural limitations determine the kinds of plants and animals that can successfully complete their life cycles year after year and the level of biomass production that can be attained. For example, within an ecosystem solar energy is captured and flows from plants to animals to microorganisms. Essential soil nutrients are mobilized in plant and animal tissue and returned to the soil through decomposition by the microorganisms in an unending nutrient cycle. Surface-mining activities disrupt this cycle and the interconnections that are vital to an ecosystem. Successfully reestablishing the natural or provisional ecosystems requires the rebuilding of an intricate balance between many complex processes, all of which may be affected by the climate.

Climate has often been viewed as the average weather conditions based on a certain number of years of weather observations. This is a common misconception which has at times resulted in a lack of understanding of the effects and impacts of climate, which is much more than just an average state. Climate encompasses the variability and extremes of several elements (temperature, precipitation, solar radiation, etc.) which separately or together influence all of the many complex hydrologic, biologic, and ecologic processes affecting reclamation. Some climatic elements play more significant roles than others in influencing these processes. Determining the pertinent climatic elements and their characteristics critical to reclamation can occur only after assessing the sensitivity of specific reclamation activities to climate. Therefore, in developing a climatic profile it is imperative to first isolate the reclamation activities which will be responsive to climate.

In the ensuing sections the reclamation activities are defined, followed by discussions of the hydrologic, biologic, and ecologic processes important in reclamation. Finally, the climatic elements critical to these processes are identified.

Reclamation Activities

Reclamation activities include all the steps necessary to reestablish a vegetative community following the mining process. Although there may be some variation of the sequence of steps involved, the basic sequence has been identified and includes the following:

1) Vegetation selection (see Table 1, Plant Requirements for Vegetation Selection)
2) Spoil placement and grading
3) Topsoil placement
4) Surface treatment
5) Soil preparation
6) Planting (or transplanting)

Table 1. Plant Requirements for Vegetation Selection

	CLIMATE ELEMENT															
	Elevation Above Sea Level	Long Term Mean Annual Air Temperature	High Temperature Extreme	Hottest Temperature Experienced Every Year	Low Temperature Extreme	Coldest Temperature Experienced Every Year	Freeze-Free Period	Potential Thermal Growing Season (Probability = .5)	Growing Degree 40° F Base	Annual Precipitation	Driest Years (Probability = .10)	May-September Total Precipitation	Driest Summer (Probability = .10)	October-April Total Precipitation	Driest Winter (Probability = .10)	May-September Potential Evapotranspiration
PLANT	feet	°F	°F	°F	°F	°F	Days	Days	Degree Day	Inches	Inches	Inches	Inches	Inches	Inches	Inches
Climatic Profile McCallum Study Area*	8300	36	91	83	-49	-20	35	156	not yet computed	11	8.00	6	3.50	5	3.00	22
Plant 1																
Plant 2																
Plant 3																
. . . . .																

* Estimates made for the McCallum Study Area based on Walden and other North Park data.

Reclamation activities are shown in the first column in Table 2. Additional measures required after planting, assuming successful germination and establishment, are maintenance (reseeding small areas and fertilization) and vegetation management (where the land is promptly put into production).

Hydrologic Processes

The key hydrologic process of major importance to mining activities is infiltration--the process through which water (rain or snowmelt) enters the soil. The rate at which infiltration proceeds is controlled by the rainfall or snowmelt rate, the soil surface conditions, the surface soil texture, and the soil water content. The rainfall rates of a region are a function of the storm types characteristic of the local climate and cannot be controlled. Surface conditions refer to the amount and distribution of plant litter and protective rock fragments that attenuate the rainfall-impact energy and reduce soil splashing and sealing on the surface. A secondary feature of the soil surface that enhances infiltration is the roughness of the surface or the microtopography. An irregular "rough" surface temporarily detains runoff and affords the opportunity for water to infiltrate over a longer period of time.

The texture of the soil surface, principally the clay and silt fractions, determines how easily the surface is sealed. Without a protective covering of litter, raindrop impact from intense rainfall rates destroys soil aggregates and disperses the clay particles. These particles seal surface pores which dramatically reduces the infiltration rate.

Soil water content influences infiltration in two related ways. At low soil water content, capillary forces are very high, and water is rapidly pulled into the soil like a blotter. As the soil water content increases, the capillary forces diminish steadily. When the soil is saturated, the capillary forces are zero. When this occurs, the infiltration rate is limited by the hydraulic conductivity of the saturated soil layer. If surface sealing has occurred, the saturated soil layer may be only a fraction of an inch thick. In situations when the surface has not been sealed (during snowmelt) the saturated thickness of the soil may be several feet. In either case, infiltration proceeds at its minimum rate.

The amount of water that infiltrates into the soil is of vital concern to the plants. The amount of water that does not infiltrate becomes overland flow and creates additional disruptive problems which affect the stability of the plant community. Overland flow is the hydrologic process that provides the energy for detaching and transporting soil particles which results in surface erosion. If unchecked, overland flow concentrates into channels which initiate rill erosion, which is followed by gully erosion. Erosion washes seeds away, exposes the roots of small seedlings, buries seeds too deep to emerge, removes soil nutrients and provides a pollution source for lakes and streams. These consequences of reduced infiltration rates proceed in the cycle of fewer plants, less soil surface protection

Table 2. CLIMATE ANALYSES FOR RECLAMATION

Reclamation Activity	Problems/Opportunities	Climate Analyses
I. Vegetation Selection	1. Establishment and survival of plants	1, 2, 5, 6, 7, 8, 10, 12, 13
II. Spoil Placement and Grading	<u>Problems:</u> 1. Transport by wind and runoff --shape, orientation, height --surface roughness --particle size 2. Road location and construction --snow accumulation --drainage --slope <u>Opportunities:</u> 1. Create microclimate favorable to vegetation --control wind --enhance snow accumulation --reduce evapotranspiration	4, 7, 8, 9, 10, 11, 13, 14, 15
III. Top Soil Placement	<u>Problems:</u> 1. Transport by wind and runoff	4, 8, 10, 11, 14, 15
IV. Surface Treatment (pitting, imprinting, contouring, disking, and raking)	<u>Problems:</u> 1. Control surface runoff and erosion 2. Trafficability <u>Opportunities:</u> 1. Provide favorable germination sites 2. Increase soil water	4, 8, 9, 10, 11, 13, 14, 15
V. Soil Preparation	<u>Problems:</u> 1. Trafficability <u>Decisions:</u> 1. Mulching --soil depth, water capacity 2. Supplemental water 3. Fertilizer --soil character	4, 6, 7, 8, 10, 13
VI. Planting	<u>Problems:</u> 1. Trafficability 2. Timing for seeding or transplanting --germination --growth and establishment 3. Seeding rate	1, 2, 3, 6, 7, 8, 10, 12

<u>CLIMATE ANALYSES</u>

1. Freeze-Free Period.
2. Growing Season.
3. Late Warm Periods.
4. Freezing Temperature Threshold.
5. Extreme Temperatures.
6. McCallum Site Precipitation.
7. Annual and Seasonal Variability
8. Precipitation Frequency and Intensity.
9. Snowfall Frequency and Intensity.
10. Snow Accumulation and Snowmelt.
11. Large Rain Events - Return Periods.
12. Growing Season - Joint Probability.
13. Growing Season Potential Evapotranspiration Minus Total Precipitation.

*14. Frequency Distribution of Wind Speed and Direction.

*15. Probability of High Winds.

* Not available due to lack of data.

and infiltration, more overland flow and erosion, and fewer plants until the ecosystem is destroyed. With the exception of soil surface conditions, the factors that determine infiltration are beyond control--rainfall rates, soil texture, and soil water content. Mitigating the effects of surface disturbances associated with mining activities is the primary concern in reclamation.

Biologic Processes

Natural ecosystems are comprised of plants and animals that are able to successfully complete their life cycles within the constraints and limitations of the physical environment. The life cycle for plants begins with a viable seed that germinates, becomes successfully established, proceeds through growth and development, flowers, and finally produces viable seeds. Animals have similar life cycles that begin with birth of an offspring, proceed through growth and development, then successful reproduction. Because revegetation is of prime importance when reclaiming mined lands, the following discussion will deal only with the important biologic processes of plants.

Seed germination is a biologic process that includes a number of individual biochemical processes that are activated within a seed when seed moisture content and soil temperature are simultaneously within the ranges required for the biochemical processes. During germination, the seed imbibes water and the primordial root and shoot begin development. The root elongates and the shoot emerges from the soil. Development continues until the energy reserves of the seed are exhausted. At the same time that seed food reserves are being used, the seedling is also beginning to establish its independence by taking up nutrients directly from the soil and by producing carbohydrates through photosynthesis.

"Establishment" is the term commonly used for the critical time period when the seedling is making the transition from its dependence on the energy reserves in the seed to its dependence on its own root and shoot system to manufacture carbohydrates. If soil water, soil and air temperatures or soil nutrients are limited during this time, the seedling will not survive and the life cycle will be interrupted.

Photosynthesis is the process through which plants capture solar radiation and convert the radiant energy into chemical energy (carbohydrates), which is used to fuel all the processes for growth and reproduction. Once a seedling has become successfully established, root and shoot development are rapid as long as soil water and soil and air temperatures are not limiting. The extension of the root system to deeper soil depths where the soil water availability is less variable than at the surface is a major factor in survival.

The efficiency of photosynthesis is closely coupled to air and soil temperature and soil water availability. Air and soil temperatures can be too

high for plant survival, even when all other conditions are optimal. Although the optimum air temperature for photosynthesis varies for different plant species, many temperate plants photosynthesize at their maximum rate when the air temperature is in the range of 70° to 90° F when soil water is freely available. Soil water is considered to be freely available at water content near "field capacity." As soil water availability decreases toward the "wilting point," photosynthesis is drastically reduced. Although photosynthesis can continue for some plants when the soil is very dry, plant growth has virtually ceased and the plant is only "surviving."

The biologic process of respiration is the complement of photosynthesis. Photosynthesis is the production-of-energy process and respiration is the utilization-of-energy process. If ambient temperatures are optimum for respiration but suboptimum for photosynthesis, the rate of respiration exceeds the rate of photosynthesis and the plant goes into an energy deficit. If such ambient conditions continue, the plant eventually dies.

Vegetative growth is the continuing process of enlargement of the root and shoot systems. During continued growth, the plant redistributes carbohydrates to different plant parts. In grasses, the roots and crowns are important sites for carbohydrate storage.

Reproduction is the vital plant process that includes flowering, fertilization, and seed production. Reproduction in plants is also accomplished by vegetative means--where new shoots arise from underground plant parts rather than from seed. Reproductive growth is initiated by the total duration of light (usually the relative length of the night and day). When day length is appropriate, reproductive growth is initiated. Instead of directing the carbohydrates to the leaves or the roots, the plant directs the energy to flower production and organ reproduction. Flowers develop and after fertilization seeds are produced and the life cycle is completed.

Transpiration is perhaps the most integral process of the plant. Root uptake of soil water and nutrients as well as photosynthesis cannot proceed in the absence of transpiration. Transpiration differs from evaporation because it is controlled by biologic mechanisms. Carbon dioxide exchange occurs through stomata in the leaves. At the same time that CO_2 is entering the leaf, water vapor is lost to the atmosphere. Stomatal mechanisms brought into action under periods of stress close the stomatal openings and reduce the rate of transpiration. Transpiration is a function of the continuum of the potential water gradient--soil-root-stem-leaf atmosphere. The potential water gradient is driven by the atmospheric water vapor deficit, or more commonly, the potential evaporation rate.

The potential evaporation rate is a process that is entirely controlled by the climatic elements of water vapor, energy, and wind. Because soil water is not freely available, actual evapotranspiration (ET) rates are rarely equal to potential ET rates in semi-arid climates. In reclamation areas, plant establishment is particularly sensitive to potential ET rates. Young seedlings do not have well-developed root systems. Unless soil water is

not limiting, high potential ET rates can quickly "dehydrate" a young plant and result in its death.

Nutrient uptake is an important plant process that is essential to successful plant establishment; it is a function of soil water uptake and the relative concentrations of the essential plant nutrients in the soil. Provided that nutrients are present, a plant's uptake rate is also controlled by the chemical form of the nutrient and the pH of the soil solution. Particular problems arise in reclamation success that are traceable to problems related to nutrient availability.

Ecologic Processes

Three ecologic processes important to revegetation are: (1) competition, (2) succession, and (3) nutrient cycling.

(1) Competition is the process in which plants compete for resources (water, space, and nutrients) in short supply. Competition can result in low biomass production and poor plant establishment of the seeded species if the initial seeding rate is too high. For example, if the seeding rate results in high seedling density, the seedlings will "compete" with each other for the soil water, which results in reduced seedling size, poorer overall vigor of the plant stand, and perhaps in a seeding failure. Competition also exists for plants of different species. Plants differ in the time of germination and establishment, rate of root and shoot growth, and root distribution form; i.e., some plants rapidly develop tap roots that extract soil water at deeper layers, some develop fibrous root systems that extract soil water in the shallow surface layer, and some develop root systems with both characteristics. Recommended seed mixtures are selected to minimize competition between species. However, weed species are fierce competitors which can "invade" a newly established seeding and completely replace the originally seeded stand.

(2) Collectively, the changes in the composition in plant communities over time is called "succession." Competition over time results in replacing the seeded stand by different species. This "selection" process is natural and sometimes beneficial. In the development of an ecosystem, succession results in an assemblage of plant species that "match" the limitations of the physical environment. The resulting assemblage of plants coexists as a stable ecosystem and the biomass production is usually near maximum for the particular environment.

(3) Nutrient cycling is a process characteristic of the ecosystem as a whole. Plants take up required nutrients from the soil and immobilize the elements in plant tissue. With the senescence and death of leaves and roots, the dead plant material is decomposed by the microorganisms in the soil, and the nutrients are returned to be used again.

Two factors must be considered regarding nutrient cycling. (a) Since nutrients taken up by plants are stored in plant tissue for varying lengths of time, the reserve supply of nutrients in the soil must be large enough

to continue to supply nutrients to the growing plants until the nutrients are returned through decomposition. The decomposition rate is a function of the soil temperature, the soil water content, and the chemical composition of the plant material. If the decomposition rate is slower than the uptake rate, the ecosystem production will decline, individual species will disappear, and the composition of the plant community will revert to only those plants whose uptake rates are "in balance" with the rate of nutrient supply. In most ecosystems, these plants are weed species. (b) Topsoil depth is by far the most critical reclamation factor in successful revegetation. A measure of the size of the nutrient pool is the depth of topsoil; if it is too shallow and decomposition rates are slow, nutrient limitations will often be reached by the second or third year after seeding.

Hydrologic, biologic, and ecologic processes are intimately coupled in an ecosystem. Climate characteristics and their variation assume the roles of forcing functions that "cause" the various processes as well as determine the rate of the processes. The climatic extremes definitely circumscribe the limits of ecosystem development in terms of the species that can continue to remain on a revegetated site and the level of biomass production that can be realized. The problem that is faced in reclamation is essentially one of speeding up the natural process of succession so that a stable plant community is reached in a shorter period of time than it would take under natural conditions. Proper seed selection and planting procedures, restoration of the soil water balance necessary for establishment and growth, and reestablishment of the nutrient cycle are the essential requirements for successful revegetation. The overriding control of all the processes by climate characteristics presents substantial risks beyond man's control.

Critical Climatic Elements for Reclamation

Critical climatic elements are those elements that affect reclamation activities either directly or indirectly. Directly implies that the climatic element influences the activity by its presence. For example, snow affects nearly all equipment by restricting trafficability. Indirectly implies that the climatic element influences the activity through its interrelationship with either the energy or water balance. For example, cold temperatures result in frozen ground; this affects the preparation for seeding. The indirect category usually results in an impact which can be quantified by combining climate with other disciplines.

The interaction of the climatic elements in the energy balance and with the hydrologic processes results in a dynamic physical environment with a range in variation. Plants must be able to survive within this range in variation, which must be considered in terms of daily, seasonal, annual, and longer time scales. Analysis of the critical elements in climatic records can provide useful criteria in the form of statistical descriptors that can be used to assist in selecting plants that are most likely to be established successfully and to assess the difficulties of maintaining the vegetative cover.

Plant processes operate within a range of variation described with cardinal values of a particular climatic element, such as air temperature. There are three cardinal values; (1) the minimum below which the process ceases to function, (2) the optimum at which the process proceeds at the maximum rate; and (3) the maximum beyond which the process ceases to function. Cardinal values vary with different plant species. While these values are known for virtually all agricultural crops, in only a few cases have the values been determilned for native plants that are used in revegetation. Until more information is available, plant selection for revegetation must continue to be guided by modifying the results of past experience and research. However, in the absence of specific information about cardinal values, general knowledge is useful to compare to climatic element variation.

The primary elements of climate for reclamation are precipitation, air temperature, solar radiation, humidity, and wind. These elements can act directly, indirectly, and in combinations to affect reclamation activities.

1. Precipitation. Precipitation (both snow and rain) is the most important climatic element. The annual and growing season precipitation amount and the year-to-year variations largely determine the success or failure of revegetation. If during the period of seedling establishment the precipitation is greater than the potential evaporation, soil water is available to promote rapid root and shoot growth which will favor survival. The frequency distribution of the daily amounts of precipitation during the growing season is important. If the most frequent daily amounts are equal to or less than the potential evaporation, net water available to the surface soil horizon is zero. It is the surface horizon where conditions of temperature and soil water are critical to germination and establishment. Deeper soil layers are less subject to wide variations of temperature and water than the surface is. Once roots have penetrated to these less variable layers, daily rainfall amounts are not so critical. For semiarid sites, it is known that events of less frequent daily amounts which are greater than the potential evaporation are the only events significant to the water balance. Only in situations when small daily amounts occur in an unbroken series of consecutive days do these amounts contribute to the soil water.

High rates and large amounts of precipitation are the sources for erosion and runoff which is a major problem in many geographical areas. Probabilities of large precipitation events are used for design purposes.

Snow is an important feature in many areas; it is a problem for trafficability and runoff, a source of soil water, and a protective layer for vegetation. Combinations of snow and wind offer an opportunity to manage snow accumulation to enhance soil water and reduce traffic problems.

2. Air Temperature. The annual variation of air temperature determines the period of time in the year that air (and soil) temperatures are above the minimum cardinal temperature for photosynthesis, nutrient uptake, and respiration. The level of the temperature itself defines the frost-free

period as well as the number of degree-day heat units necessary for complete plant development. The daily variation of air temperature during late fall and early winter, i.e., warm days above freezing and cold nights below freezing, can cause high transpirational stresses that cannot be met by the soil because water uptake is so slow at cold temperatures. When these conditions exist, the familiar winterkill occurs.

3. Solar Radiation. Solar radiation directly affects plants through the quantity of energy reaching the ground with wavelengths between 0.4 μ and 0.75 μ, the band of wavelengths that is important to photosynthesis. Total incoming radiation is partitioned at the surface through the energy balance which results in the critical climatic elements of air and soil temperature and latent energy. Latent energy, the component of the energy balance related to evaporation, is the component that couples the energy balance and the water balance in terms of evaporation and transpiration. Solar radiation is a critical climatic element, not only as the driving variable of the energy balance, but also because it establishes the relative length of day and night for a particular latitude. Day length is important to plants because its variation determines whether or not flowering will be completed. For some plants, a short day length is critical to complete development, while for others, a long day length is required. The intensity of solar radiation stimulates the guard cells to open, which opens the stomata, increasing the rate of transpiration. Since the intensity of solar radiation reaching the ground may increase with elevation, transpirational stress could be higher for newly established plants at high elevations. Since temperatures follow the same course as solar radiation through the year, solar radiation influences the length of the growing season.

4. Humidity. Humidity has an indirect role for reclamation since the water content of the atmosphere controls the water vapor pressure, which plays a major role in evaporation and evapotranspiration.

5. Wind. Direct effects of wind are those related to wind erosion, evaporation, air pollution problems, and snow distribution.

6. Joint Occurrences of Climatic Elements. Precipitation and temperature are combined because either one can limit biologic processes. For example, during late winter--early spring, soil water may be appropriate for germination or growth, but soil temperatures are below the minimum cardinal temperature. In such situations, germination (or growth) does not occur. Analyses that consider the joint variation of temperature above a given threshold and precipitation above a given threshold can be carried out to characterize the conditions for germination or development during the growing season.

Precipitation, temperature, wind, solar radiation, and vapor pressure combine with vegetation and soil conditions to determine the potential and actual ET rates, which are the crucial elements in the water balance. Actual evapotranspiration controls the revegetation success in semiarid climates.

The brief discussions above have touched on ways in which critical climatic elements influence revegetation. However, climatic elements seldom influence plant growth independent of the hydrologic processes or the physical properties of the soil. The characteristics of the hydrologic processes and the physical properties of the soil may entirely negate what might seem to be the "ideal" variation of the climatic elements by themselves. Soils especially determine to a great extent the success of revegetation.

CLIMATIC DATA SOURCES AND QUALITY

All climate profiles require high quality climatic data as the primary input. The first step towards the actual preparation of a climate profile for reclamation is locating climatic data for the area of interest. While this may seem straightforward, problems arise because data are collected by assorted Federal, State, and private organizations. As a result, data are not necessarily archived together, data quality may vary considerably depending on the source, and it may take a substantial effort to locate and acquire all available data.

There is a rational method for approaching the problem of locating appropriate data sources. To begin with, it is necessary to recognize and rank the most likely sources of data and to determine what climatic elements are probably being measured. Secondly it is important to know who archives these data, where the data are kept, how accessible the data are, how much is known about the quality of the data, and how much climatic summarization has already been done with the data.

A condensed presentation of the most likely data sources is shown in Table 3. This list is not exhaustive, but it does contain those groups responsible for the vast majority of climatic data collected in this country. Data sources vary from state to state depending on several factors such as predominant economic activities, amount of Federal lands, and special climate-related local problems. These variations are not reflected in Table 3, but this should not detract from its general usefulness.

Table 3. Climatic Data Sources.

FEDERAL	STATE AND LOCAL	PRIVATE
Dept. of Commerce NOAA - National Climatic Center 1. Cooperative substations 2. First order stations 3. Second order and aviation stations 4. Evaporation stations 5. Solar radiation stations 6. Upper air stations	Dept. of Natural Resources (or equivalent) 1. Special networks Dept. of Air Quality (or equivalent) 2. Air quality and weather State University 3. Field stations Local Muncipalities and Water Districts 4. Special surface weather stations	1. Major Industries 2. Media 3. Mines 4. Utilities
Dept. of Agriculture Forest Service 1. Fire weather network 2. Storage gage network Soil Conservation Service 3. Snow courses and SNOWTEL Science and Education Administration 4. Field stations		
Dept. of Interior Geological Survey 1. Streamflow 2. Special watershed studies 3. Special studies--Oil shale Water and Power Resources Service 4. Research Programs Bureau of Land Management 5. Storage gages 6. Special Studies National Park Service		
Dept. of Defense Air Force, Army, Navy 1. Weather stations Corps of Engineers 2. Reservoir stations		

National Weather Service--National Climatic Center

The appropriate starting point in locating climatic data sources will practically always be the National Weather Service (NWS) networks. Their data are generally available in many forms and can be acquired, in varying extent, from several sources. Nationally, there should be one weather station measuring both daily temperatures and precipitation for every 625 square miles in the United States. This is not always the case, particularly in areas of complex terrain where potential sites and potential weather observers are few and far between. However, this is generally the most standardized, most accessible, and most used data set even though it is usually limited to only temperature and precipitation.

The NWS network of first-order weather stations (which are manned 24 hours a day) can be a very valuable data source, containing wind, humidity, and cloud data as well as temperature and precipitation on an hourly or three-hourly basis. There are approximately 250 of these sites in the United States; they are usually located in or near major cities and are seldom located in the vicinity of BLM lands.

Similarly detailed data are collected at a number of second-order NWS weather stations and also several weather stations operated by the Federal Aviation Administration (FAA). Unfortunately, summarization of most of these data is not routinely performed and, hence, the data are not easily useable.

Special observational networks such as the upper air and solar radiation networks are operated and maintained by the NWS. Evaporation and soil temperature data are also collected at a few sites.

Although these special networks have a very limited station density, they do supply valuable information on several climatic elements which are not readily available from other sources.

The NWS data sources offer many advantages to the climate information users. Some data are always currently being collected or are available for past years in the general vicinity of any specific location in the country. (The exception is high elevation mountain locations where very few NWS stations are located.)

One of the greatest attributes of the NWS climatic data sets is availability. Most of the data are published in standard data periodicals. Data are all archived at the National Climatic Center (NCC) in Asheville, North Carolina. Many of the data sets have been digitized and are available from NCC on magnetic tapes along with appropriate documentation. In addition, much of the data have already been assembled into a variety of summarized forms, which contain long-term averages of such parameters as monthly temperature, precipitation, and heating degree days, have been prepared for many nationwide locations.

Because of the concerted effort to publish and disseminate pertinent climate information, NWS data can be obtained without having to contact NCC. For example, many states have active State Climatology Offices which maintain NWS records and computerized data archives for their individual states. Some NWS climate information for a given area can also be obtained directly through the local NWS office. Finally, major libraries often subscribe to NCC climatological data publications.

Other Federal Agencies

Many other climatic data sources exist. Several Federal agencies have special responsibilities which require the collection of climatic data in addition to that collected by the NWS. In the Rocky Mountain West, the Soil Conservation Service (or the state, as in California) collects high elevation snowpack data to help predict riverflows and water supplies throughout the year. This excellent winter data set yields considerably useful information on the winter precipitation climate of remote, high elevation areas. Monthly snowpack data are maintained on an active computer system and are easily summarized and made available. While this is an extraordinarily useful data set, it is limited because data are only collected during winter and early spring.

Another major collector of climatic information is the U.S. Forest Service. Special fire weather stations are located throughout Forest Service lands across the country. Detailed temperature, precipitation, humidity, and wind data are collected during the summer months to help monitor forest fire potential and are promptly archived and maintained in a compatible computer form.

Other activities within the U.S. Forest Service's broad scope of responsibilities also involve data collection. Precipitation storage gages are operated in some remote sites to monitor annual precipitation on Forest Service lands. Winter snow and wind conditions are measured in mountainous areas to support avalanche forecasting and warning activities.

The U.S. Geological Survey is another collector of climatic data. While their major data collection responsibility is measuring flow rates of rivers and streams across the entire United States, they also participate in an assortment of other data collection activities; for example, their role as overseers of the Federal oil shale tracts in the West has led to extensive basic climatic data collection.

The Department of Defense is a special source of climate information for many areas. Near most Army, Air Force, and Navy installations across the country, detailed climatic information is collected, assembled and used for a variety of purposes. Much of this information, while not made as publicly available as NWS data, can be obtained, often in summarized form.

Other Federal agencies collecting climatic information include the Bureau of Reclamation, the Bureau of Land Management, the National Park Service,

the Agricultural Research Service, and the Corps of Engineers. These groups frequently act as cooperative observers for the NWS; therefore the data are stored in NCC archives and publications. However, special projects and special studies performed by these agencies often lead to data collection. Thus, if any of these agencies are located near or have jurisdiction over an area it may be worth pursuing through local contacts to find out if any local climatic data have been or are being collected.

State Agencies

States generally rely on federally collected climatic data to meet their information needs. However, some states with special climate-related problems have undertaken their own data collection programs. The type of state agencies most likely to be involved in data collection, archival and analysis are those related to natural resources, air and water quality, and/or environmental protection. Local contacts must be made in each state to help determine what climatic information collection is being performed.

Local Agencies

Local municipalities and water districts also sometimes choose to collect their own climatic information. Again, local contacts must be made (or information can sometimes be obtained from the State Climatologist or the local NWS office) to determine what data are being collected.

Universities

Universities, especially state land-grant institutions, are often excellent sources for climatic information. Agricultural experiment stations and other university-related field stations often collect detailed long-term climate data. While these data are sometimes supplied to the NWS and NCC, additional data are frequently available. Other university research, particularly related to agriculture, plant and animal life, energy, and atmospheric science, may lead to local or regional climatic data collection. Local contacts must again be found to help track down the availability and accessibility of related data.

Private Sources

Finally, climatic data collection is not limited to public and governmental groups and agencies. Many private businesses, industries, institutes, and occasionally individuals participate in data collection for a variety of purposes. In some cases, Federal and State regulations require onsite environmental monitoring. In other cases, utilities, businesses, and industries have their own special data needs. Private consulting firms are often called upon to conduct these data collection programs. To locate private sources of climatic information requires the effort of contacting utilities, mines, major industries or any other likely source near the area of interest. (A word of caution: Data collected by private concerns are not always available to the public.)

While there are many potential sources of climatic information, there is never complete certainty that adequate data can be found for a specific area to develop a complete and totally representative climate profile. This is especially true in sparsely populated areas with complex terrain where climatic information may be equally sparse. Spatial variability and representativeness of climatic information, described in detail in the next section, are major concerns which help determine how much data are really needed and from what locations to adequately describe the climate of a specific area.

Data Quality

Data quality is controlled by three factors: (1) the instruments used, (2) calibration practices used, and (3) quality control after data collection.

(1). Once instruments are chosen, a program of periodic calibration is mandatory for several climatic elements including temperature, humidity, wind, and solar radiation. All instruments change with time and therefore must be serviced and recalibrated periodically.

(2). Measurements of climatological elements are not precise in many cases. For example, precipitation measurement accuracy depends on the size of the gage and on windspeed. As a result, determination of climate variation in time and space demand that one observation be compatible with other observations. The NWS has established the accepted measurement practice in the U.S. Consequently, observations taken with non-NWS accepted instruments and methods of exposure should be questioned since they may not be compatible with other measurements.

(3). Quality control of data following data collection is necessary. If data are not checked promptly it becomes increasingly difficult to go back, locate, and resolve data problems. Examination of data shortly after collection by someone familiar with the data and the area is the best practice to lead to quality data.

Groups, such as the NWS who are responsible for extensive programs of data collection, dissemination, and use, generally pay close attention to data quality. As a result, data from these sources are usually reliable and consistent. However, many of the possible data sources described here may be special purpose, limited-use data sets which are probably of short duration. The nature of these data sets is such that data quality is not always a major concern; thus, the quality, consistency, and intercomparability should always be examined and questioned. Short-duration, special-purpose data sets can prove to be very useful in assessing local small-scale, short-term climate variations. However, their limitations are great, and therefore they should not form the backbone of a climate profile.

CLIMATIC VARIABILITY

Climate and variability are two words which belong together. Important climatic variations occur both in time and space and are caused by changes in the frequency and distribution of individual weather events. It is this variable nature of climate which gives rise to the difficulties in defining climate at a particular location and designing reclamation procedures best suited to that climate.

Space Variations and Data Representativeness

Large-scale climatic controls (latitude, continentality, air-mass source regions, ocean currents) produce climates which vary gradually over large horizontal distances. Where large-scale controls dominate, the climate can be well documented based on long-term climatic data from a fairly low density of weather stations. Each station is then likely to be representative of a large area, and interpolation between stations is a valid way of estimating climatic conditions in data-sparse regions.

There are many smaller scale influences, however, which can cause rapid variations in climate over relatively short distances. The major small-scale controls include: elevation, topography (terrain, slope and aspect), soil, vegetation, urbanization, and location relative to large bodies of water. Where small-scale controls are important, it is difficult to quantitatively establish the local climate without a much higher density of climate stations. Data from a particular station may be representative of only limited areas, and linear interpolation may be an unacceptable method for estimating climatic conditions between data points.

Prior to developing a climate profile for a specific area, it is extremely important to assess the probable magnitude and extent of spatial variations in the particular region of interest. An understanding of small-scale controls and the related climate variations is helpful in determining how adequate existing climatic data may be for describing the local climate. It may point out the need for collecting additional onsite data or the need for acquiring data from all possible existing sources in the given area. Finally, knowledge of the probable spatial variations in climatic conditions can help to determine how specific the special recommendations based on local climate information can legitimately be.

1. Determining Areas Prone to Significant Spatial Climate Variations. Without examining local data, there are several ways of estimating the probable magnitude and extent of spatial climate variations. On a broad scale, perhaps the best method is to simply take a look at a topographic map. Areas of complex terrain where there are significant elevation changes over relatively short horizontal distances are locations likely to experience large spatial climatic variations. While mountainous areas are especially variable, surprisingly small elevation and terrain differences can produce significant variations (examples follow later in this section).

Another method for determining spatial climate variations is to examine national maps of such parameters as annual precipitation, snowfall, and dates of last spring or first autumn frost. These contoured maps contained in the Climatic Atlas of the United States (U.S. Department of Commerce, 1968) and other climatology reference books clearly show, in an average sense, the areas of the country where horizontal variations may be great. The greatest variations are noted in and near mountainous regions; however, significant variations are also noted in other parts of the country such as areas near large bodies of water or in the vicinity of major river valleys. The *Atlas* maps actually tend to smooth out local variations; hence, they should not be used to assess the magnitude and extent of variations. However, they are excellent guides for pointing out areas most likely to experience large variations.

Near the specific regions of interest there are additional methods for assessing climatic variations. For example, it is advantageous to visually survey the area to assess terrain variations and to note changes in vegetation. Since plants maintain a very intimate relationship with their environment, vegetation is an excellent indicator of climatic variations. Observed variations in natural vegetation are often associated with differences in precipitation, solar radiation, temperatures, and/or growing season length, but it should be noted that slope of the terrain and soil characteristics play equally important roles.

2. Characteristics and Examples of Spatial Variations. In the paragraphs which follow, brief physical explanations will be given for why several climatic elements behave as they do. The magnitude, extent, and effects of horizontal variation will then be discussed by examples. Several of the examples will be taken from a special climate summary of the North Park region of north-central Colorado (McKee, et al., 1981).*

a). Temperature. Small-scale factors can have significant effects on temperature, which in turn influences other climatic parameters such as freeze-free period and growing season which directly affect plant growth.

A common misconception is that temperatures always decrease with increasing elevation. While this is generally true of daytime maximum temperatures, particularly during the summer (Fig. 1), this does not apply at all for nighttime minimum temperatures (Fig. 2). Colder air has greater density and therefore slides downhill and fills in low depressions (analogous to waterflow). This phenomenon is referred to as drainage flow and can lead to large nighttime temperature differences over surprisingly short horizontal distances. Low spots such as river valleys or parks tend to trap cold air and record the lowest temperatures while the higher areas nearby

*This report, Climate Profile for the McCallum EMRIA Study Area, was prepared for the Division of Special Studies, the Bureau of Land Management, Denver Service Center, Denver, Colorado. It will be referred to several times in the following pages and will be designated "CPM" for Climate Profile--McCallum.

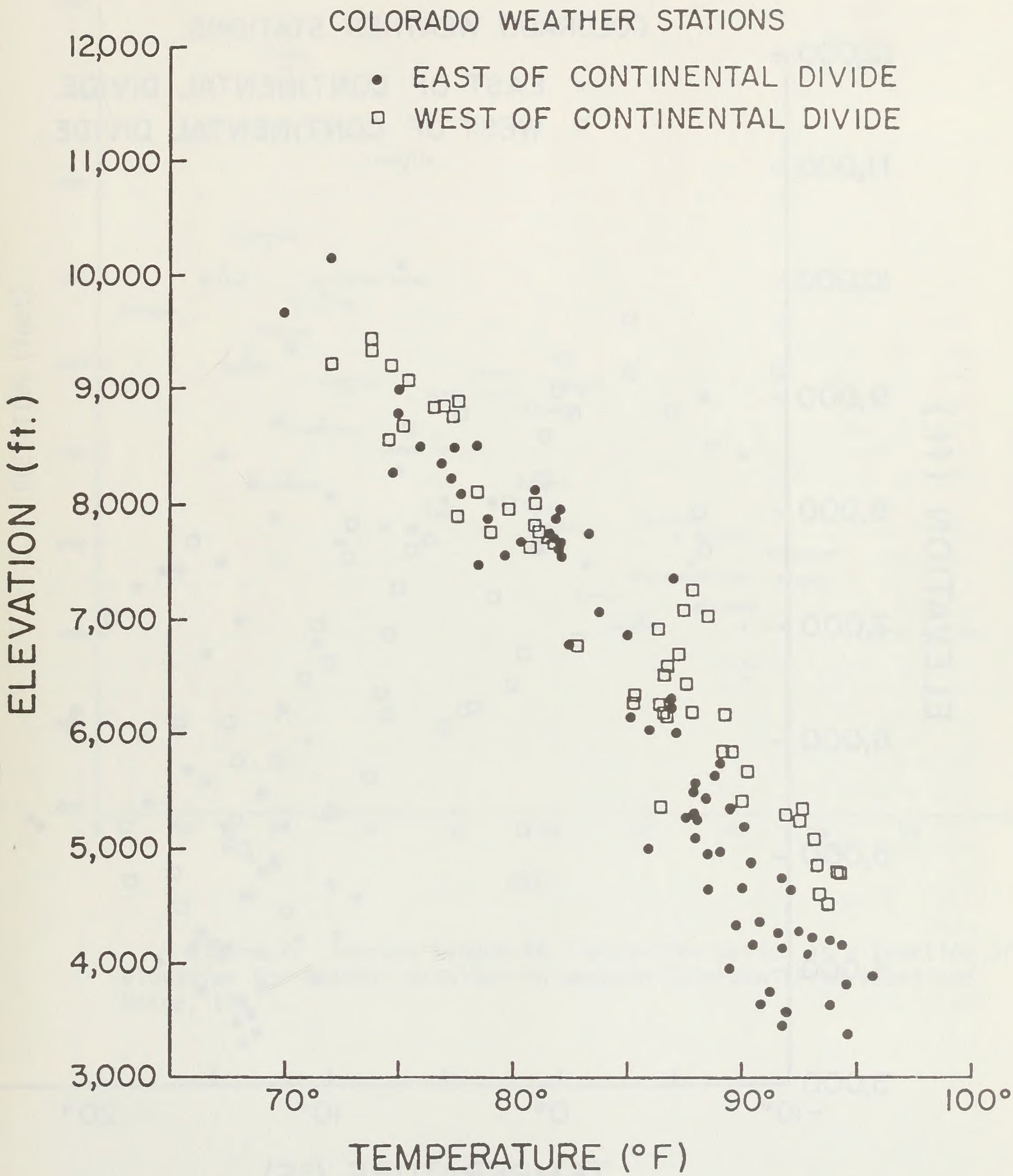


Figure 1. Average maximum temperatures in July as a function of elevation for weather stations in Colorado. (Based on 1951-1970 data.)

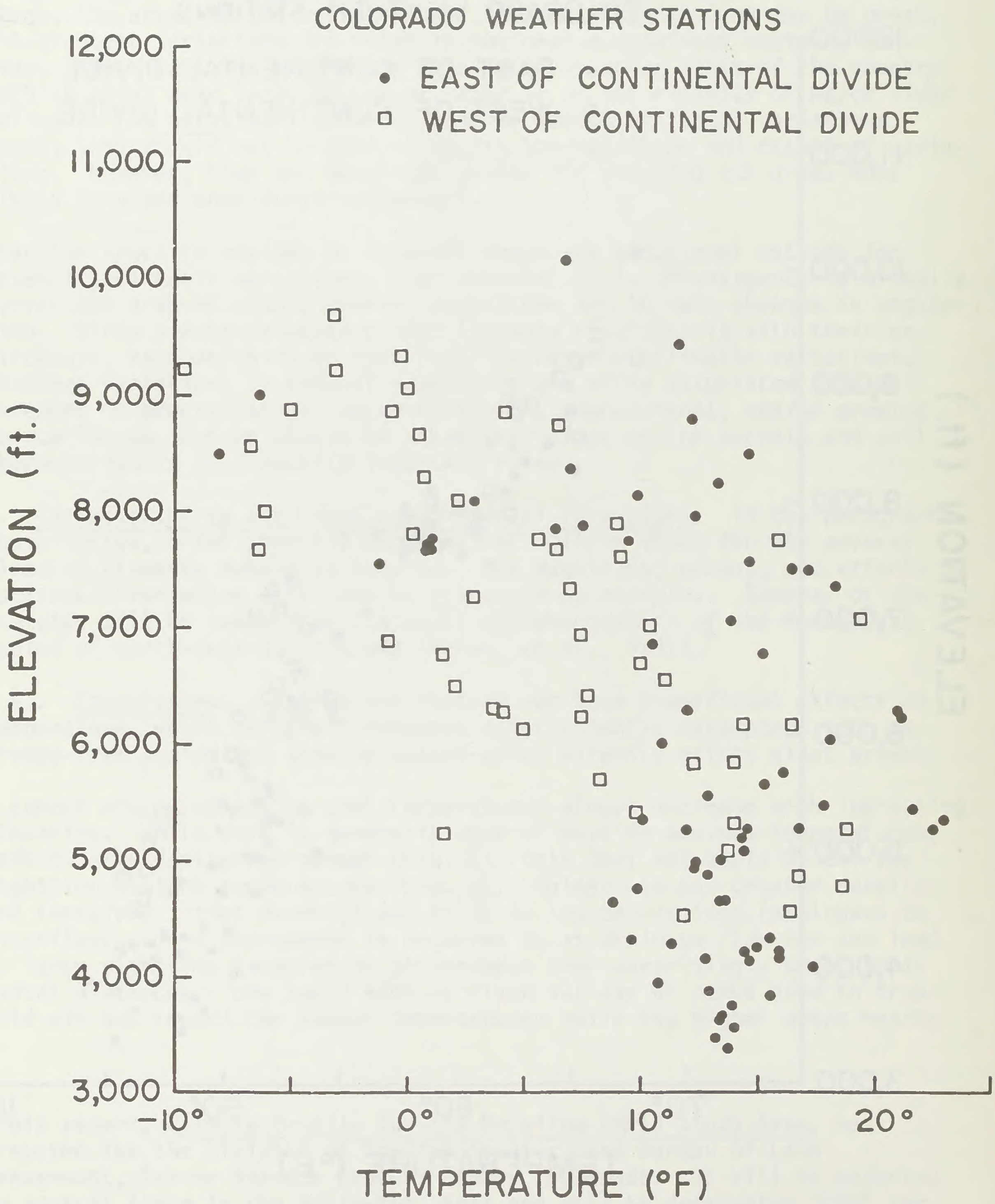


Figure 2. Average minimum temperatures in January as a function of elevation for weather stations in Colorado. (Based on 1951-1970 data.)

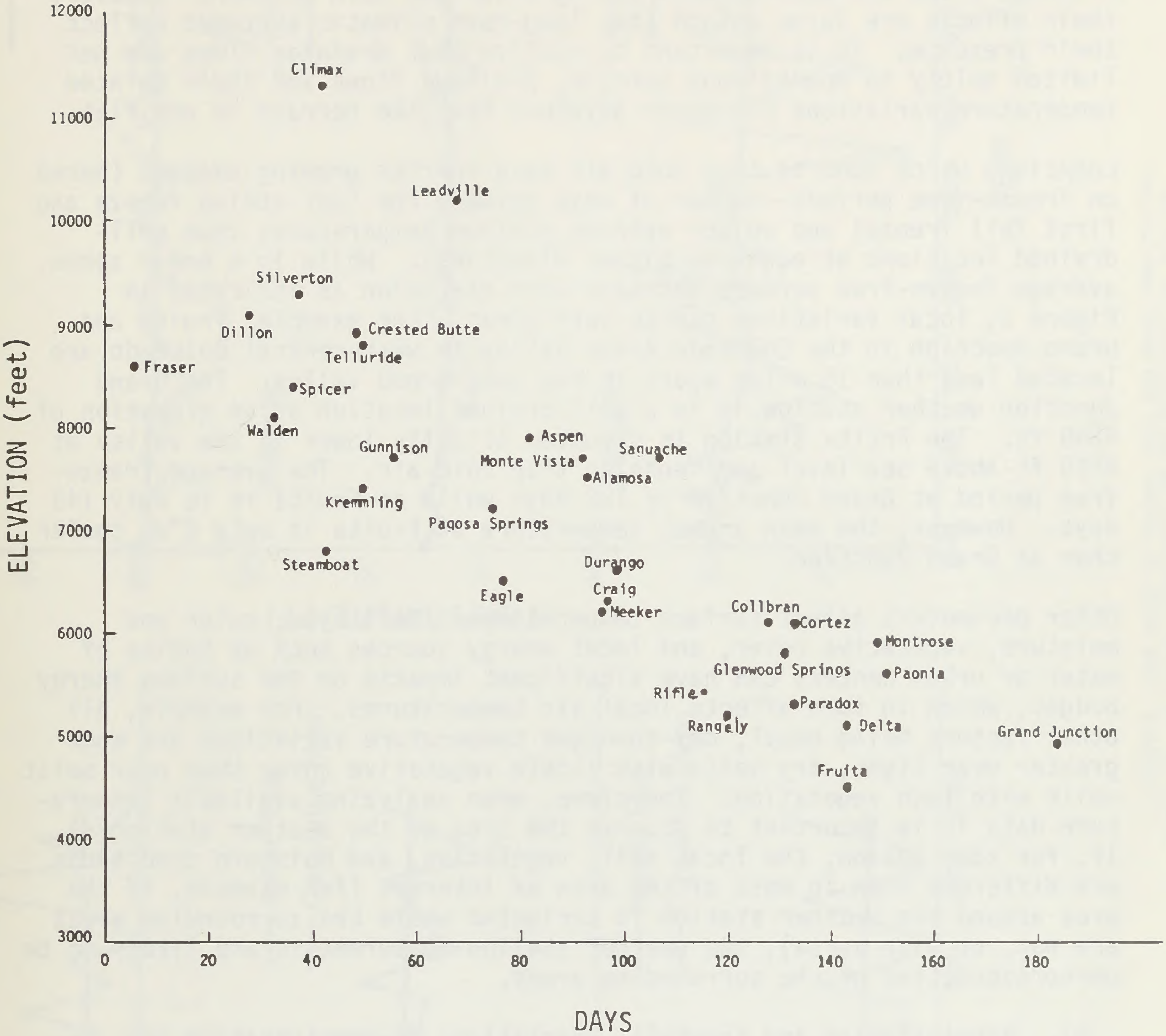


Figure 3. Average length of freeze-free period as a function of elevation for weather stations in western Colorado (from Benci and McKee, 1977).

are considerably warmer. On a given night, elevation differences of less than 100 ft can result in temperature differences of more than 3° F (Whiteman, 1980).

Drainage flows are most evident during clear and calm weather. However, their effects are large enough that long-term climatic averages reflect their presence. It is important to realize that drainage flows are not limited solely to mountainous terrain; drainage flows and their related temperature variations can occur anywhere that the terrain is not flat.

Locations which tend to trap cold air have shorter growing seasons (based on freeze-free periods--number of days between the last spring freeze and first fall freeze) and colder extreme minimum temperatures than well-drained locations at equal or higher elevations. While in a broad sense, average freeze-free periods decrease with elevation as indicated in Figure 3, local variations can be very great. For example, Fruita and Grand Junction in the Colorado River valley in west-central Colorado are located less than 15 miles apart in the same broad valley. The Grand Junction weather station is in a well-drained location at an elevation of 4849 ft. The Fruita station is situated slightly lower in the valley at 4510 ft above sea level and tends to trap cold air. The average freeze-free period at Grand Junction is 182 days while at Fruita it is only 143 days. However, the mean annual temperature at Fruita is only 2° F cooler than at Grand Junction.

Other parameters affect surface temperatures. Soil type, color and moisture, vegetative cover, and local energy sources such as bodies of water or urban centers can have significant impacts on the surface energy budget, which in turn affects local air temperatures. For example, all other factors being equal, day-to-night temperature variations are much greater over light, dry soils with little vegetative cover than over moist soils with lush vegetation. Therefore, when analyzing available temperature data it is important to observe the site of the weather station(s). If, for some reason, the local soil, vegetation, and moisture conditions are different than in most of the area of interest (for example, if the area around the weather station is irrigated while the surrounding areas are not, or vice versa), the weather station measurements are likely to be unrepresentative of the surrounding areas.

b). Precipitation and Snowfall. Variations in precipitation and snowfall, in a long-term climatic sense, are sensitive to terrain effects and ground surface conditions. Larger scale topographic features can produce significant variations in precipitation which can greatly affect reclamation activities.*

*This discussion pertains to precipitation averaged over time, not single-storm precipitation. Rain events, especially summer thunderstorms, typically show extreme point-to-point variations. However, this type of variation smooths out quickly over a period of a few months and years. It is the consistent, nonrandom, long-term spatial variations which this section addresses.

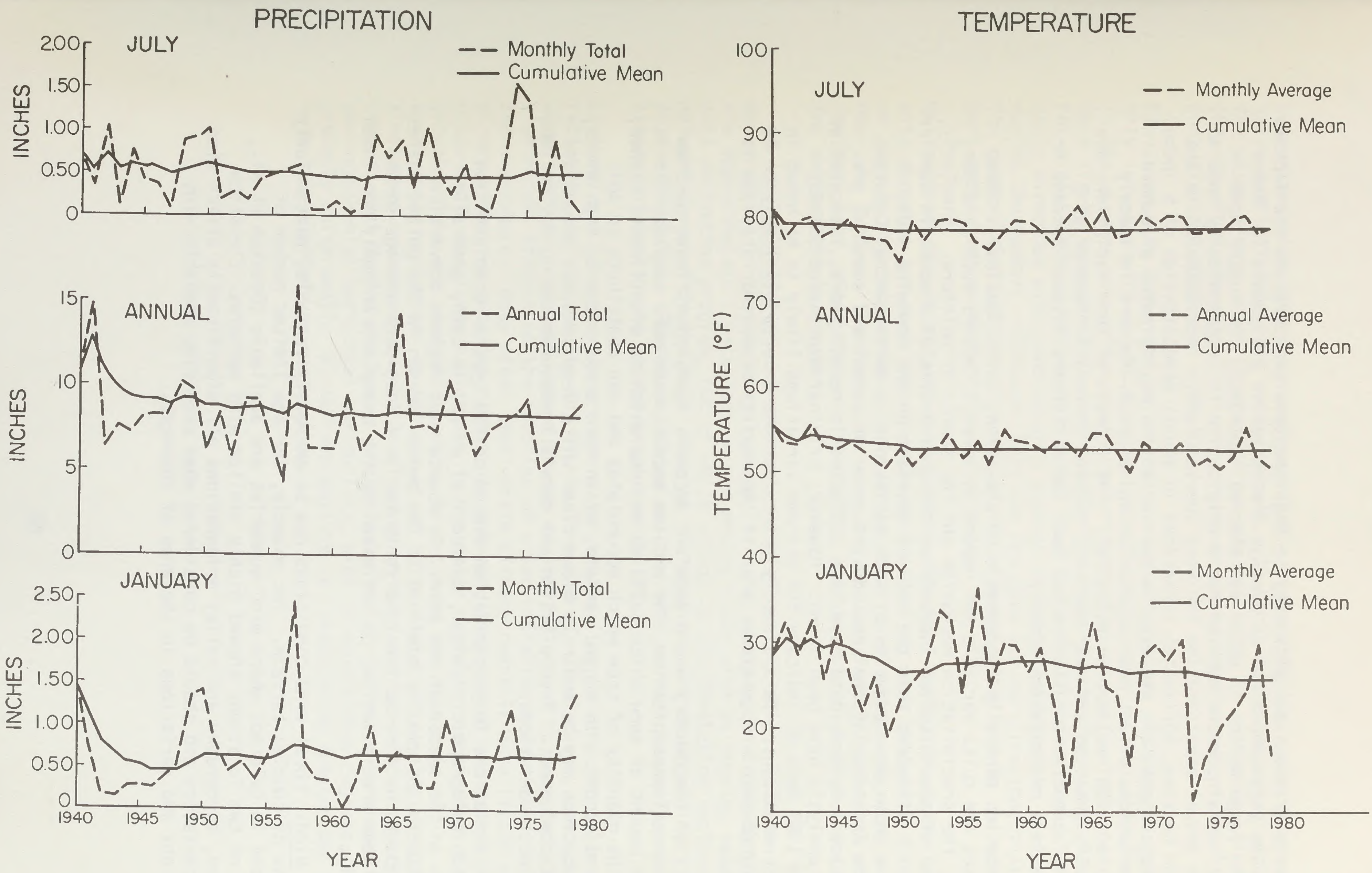


Figure 4. Time series of January, July, and annual precipitation

Relative elevations and proximity to high mountain barriers are the factors having the greatest effect on average precipitation and snowfall. Proximity to large bodies of water can also be important. In rugged mountainous terrain, where much of the precipitation is orographically induced, average annual precipitation can vary spectacularly. For example, in the Colorado Rockies, horizontal variations in annual precipitation of 5 inches per mile are possible and even larger variations may be noted elsewhere. Such variations affect both vegetation and erosion--factors intimately associated with reclamation potential. The effects of such variations are especially great in and near semiarid regions where a difference of 2 inches of annual precipitation may mean the difference between success or failure in a revegetation effort.

Precipitation generally increases with elevation, but climatically these increases are quite variable and depend on several factors such as slope, aspect, the precipitation mechanism and the source of moisture. Similarly, the rate of precipitation increase on the upwind side of a mountain barrier is usually different than the rate of decrease on the downwind side. Figure 4 shows some examples of such variations in north-central Colorado and show estimates of the areal distribution of annual and seasonal precipitation. As more data have been collected in recent years, inaccuracies in the analysis have been found. However, original maps based on 1931 through 1960 data do indicate the extreme variations likely to be noted in and near mountains. This directly points out the uncertainty likely to be encountered near a mountainous area if the density of weather stations is very low.

In parts of the country where snowfall accounts for a significant portion of the annual precipitation, the problem becomes even more complex. It is not the amount of snow which falls on an area which is significant; rather, it is the quantity of snow which accumulates and can contribute to soil water and runoff. In rugged terrain, or in open areas prone to high winds, some locations may be entirely blown clear while deep snow can accumulate in protected areas. Precipitation and snowfall measurements do not reflect these local variations.

Spatial variations in precipitation depend on the type of precipitation mechanism (orographic, frontal, convective) which, in turn, generally depends on the season of the year. In mountainous regions convective precipitation is usually confined to the summer season in the United States and tends to be more uniformly distributed in a long-term average sense than winter precipitation, as indicated by the example previously mentioned (Fig. 4).

c). Wind. Local wind conditions can be extremely variable, particularly in areas of complex terrain. For example, for the limited number of locations in Colorado where wind summaries are available (Doesken et al., 1979), no two locations showed highly similar wind patterns. Elevation, exposure, topography and valley orientations all significantly affect wind characteristics and should be considered when assessing probable wind conditions and variations in the area of interest.

Summarized wind data are rarely available with sufficient density to observe spatial variations in any detail. In fact, there are many locations for which little or no representative wind data may be available. Since this is often the case, it is important to recognize the important climatic controls that influence winds.

Elevation does have some influence on wind conditions. Windspeeds generally increase with height from the ground surface up into the atmosphere. In the absence of surface roughness effects, high elevation locations are more likely to experience winds similar to those in the free atmosphere. For midlatitude locations this means that winds usually blow from a westerly direction with considerably greater windspeeds during the winter than during the summer. Although there are few data for verification, this is the general wind pattern observed in the high mountains and in the open park areas such as North Park in Colorado.

No locations are totally free of surface effects. Surface roughness and site exposure are very important factors affecting wind patterns. Forested or heavily vegetated areas, for example, tend to dissipate the wind energy near the surface. However, over open and exposed lands, frictional effects are much less, windspeeds can be higher, and the potential for wind erosion and desiccation is greater.

d). Solar Radiation. The density of high-quality solar radiation measurements in this country is very low. For example, in Colorado there are approximately 12 stations in the entire state with an ongoing solar data collection program, two of which belong to the 39-station national network operated by the NWS. None of the stations are at high elevations in the mountains. Therefore, there are few data sources to analyze and little information to assess local variability.

Latitude and time of year are the major controlling factors for solar radiation arriving at the top of the atmosphere. Cloud cover, atmospheric water content, and dust (whose presences are influenced by topography) have significant effects on the fraction of solar radiation transmitted through the atmosphere. Many other small-scale climate controls have little or no direct effect on incoming radiation; however, local slope and aspect are responsible for large variations in the solar ratiation received at the ground. Data are currently lacking to estimate the magnitude of small-scale variations in the amount of solar radiation passing through the atmosphere. However, available cloud cover data and satellite imagery suggest that during the summer months (when solar radiation is needed for photosynthesis) horizontal variability, even in mountainous regions, is probably quite small. Winter variability is likely to be greater but may have little effect on reclamation.

e). Evaporation and Humidity. Evaporation from the ground surface (or from water surfaces) and humidity of the air above ground level are related directly to large-scale climatic controls and to the surface energy budget. Solar radiation, temperature, wind, and precipitation all have significant effects. Since humidity and evaporation rates are related closely to these other climatic parameters, some of which show considerable spatial variability, it is logical to assume that humidity and evaporation will also show significant local variation.

Detailed data on evaporation and humidity are often lacking, as was the case in the CPM study for north-central Colorado. However, estimates can uaually be made based on the more readily available data sources. For example, where temperatures are high, winds strong, and precipitation low, the humidity will be low and evaporation rates high.

f). Conclusions. The degree to which spatial variations in climate and data representativeness must be considered in a reclamation effort relates directly to how the information will eventually be used. If, in fact, few decisions will be made based on climatic considerations, then there is little reason to pursue details about local variations. However, if a concerted effort is planned to take optimal advantage of existing climatic conditions, then it is imperative to assess these variations and deal with them accordingly.

Time Variations

The large- and small-scale controls which cause spatial variations in climate have been identified and are generally understood. It is much more difficult to explain how and why climate continually varies with time. Complex interactions between oceans, land, the atmosphere, and the sun result in constantly changing weather patterns, jet streams, and storm tracks. These, in turn, produce myriad weather conditions which all define the climate.

Climate variations occur over a wide range of time scales; they begin with the day-night cycle and extend to seasonal cycles, variations from year to year, decade to decade, century to century, and longer. Of this range of time scales, the most important for reclamation are the seasonal cycle and the year-to-year variations and extremes. These relatively short time scales are critical in reclamation because they limit the types of vegetation which can grow in a given area, and they affect when and where reclamation activities can be performed.

The number of years of data (record length) needed to establish climatic averages, variations, and extremes is a problem which does not have a clear-cut solution. If there were no year-to-year climatic variations then one year of data from a given location would suffice to show day-night and seasonal cycles. But because of year-to-year differences, more data are needed. The accepted recommended record length to establish climatic means of several elements in the United States and internationally is 30 years.

However, each climatic element, such as temperature, precipitation, solar radiation, humidity, and wind, behaves differently (although not independently). Also, magnitudes of variations are a function of the time period being considered, i.e., annual averages are less variable than monthly averages, which in turn are less variable than daily averages. To further complicate the problem, elements behave differently in different climates. As a result, it is impossible to prescribe a uniform set of guidelines.

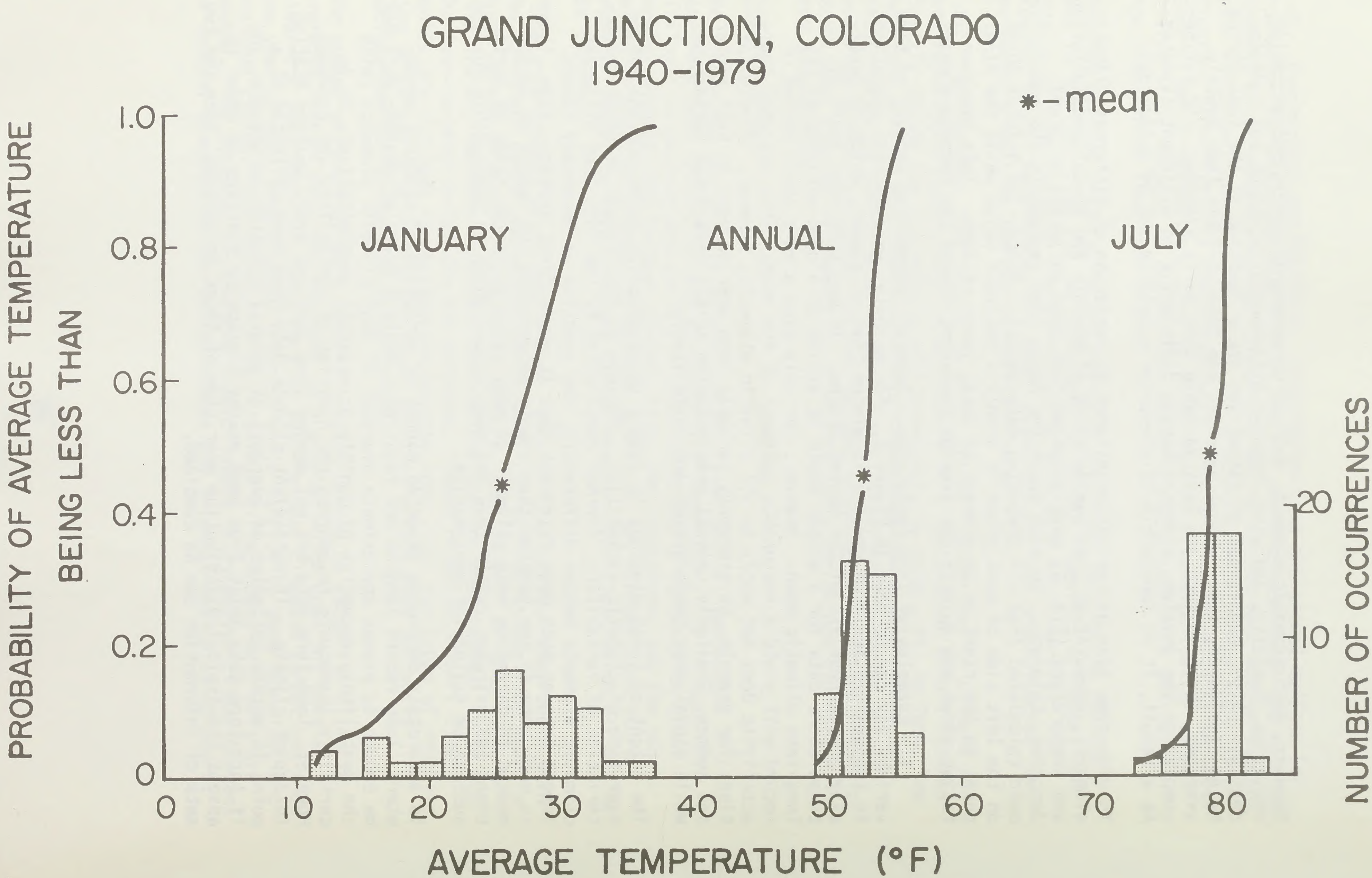
To give some idea of typical magnitudes of variation of different climatic elements, examples of time-series plots of monthly and annual precipitation and temperature (Fig. 4) were prepared from data collected at Grand Junction, Colorado. On each graph the heavy line represents the cumulative mean calculated from all preceding data points. Hence, the initial point on the left side of each graph is simply a one-year value while the final point on the right is an average of total years of data. This representation shows how quickly the average converges toward the long-term means.

1. Examples of Time Variations. Several interesting aspects of time variability can be seen in Figure 4. For example, year-to-year variations in temperature are much greater in winter than in summer, which is generally true across all of the United States. It may take many years of temperature data for a winter month to arrive at a good estimate of the long-term climatic mean. However, for July even a very short period of record will yield a reasonable estimate of the mean. This seasonal characteristic does not apply to all climatic elements, however. Precipitation, for example, is extremely variable from year to year in both winter and summer. Similarly, annual precipitation totals show large variations while annual mean temperatures are quite stable.

The intent of these examples is simply to graphically point out the nature over time of climatic variability. Because of the typical seasonal characteristics of variability, further complicated by the fact that different climatic elements behave differently, the question of necessary record length becomes much more difficult that it would first appear. Also, there is much more to the problem than simply determining the length of record needed to determine mean values. In many cases it is the range of variations and extremes rather than the mean values which is responsible for the success or failure of reclamation.

To accurately determine expected ranges of variation of climatic parameters, long record lengths are required. While 5 years of weather data may be enough to assess approximate averages of most climatic elements (with the most likely exception of monthly or seasonal precipitation), it is certainly inadequate to address the question of variability and extremes. However, long-term data are not needed from each and every weather station to depict climate. If sufficient climate data have been collected at a point to obtain estimates of averages of several climatic parameters, and if long-term data exist from some nearby station or stations in order to assess the typical distribution over time of those parameters, then the two sets of information can be combined.

Figure 5. Distribution of January, July , and annual average temperatures for Grand Junction, Colorado, 1940-1979. Number of occurrences of monthly and annual average temperatures within specified 2° F intervals shown in histogram form. Same information then shown in terms of probability distributions (Cumulative Distribution Functions).



A desirable form for viewing climatic variability where long-term data are available is in terms of probabilities (Thom, 1966). Given a set of data, such as the Grand Junction, Colorado, temperature data from Figure 4, the data points can be ranked in ascending order and presented as a cumulative distribution (Fig. 5). The shape of these distributions yields a great deal of information. For example, at Grand Junction in July, 80 percent of the years record a mean monthly temperature between 77° F and 80° F (a difference between the 0.1 and 0.9 probability level on the graph). The equivalent temperature range in January is markedly greater, ranging from 17° F to 32° F.

Time-series plots, histograms, and probability distributions are all functional displays to show climatic variations. A record length of over 20 years and preferably 40 years or more will begin to depict the nature of the variability of each climatic element. Unfortunately, even that record length is seldom sufficient to pin down the extreme high and low ends of the distribution. In fact, when applied to extreme events, no record length is guaranteed to be long enough. When considering extremes which can have especially devastating impacts, such as high winds or heavy rains, it is sometimes necessary to develop special techniques to attack the extreme value problem. There are several references such as Simiu et al., 1979, and Miller et al., 1973, which present methods and examples for obtaining estimates of value for extreme or low probability events.

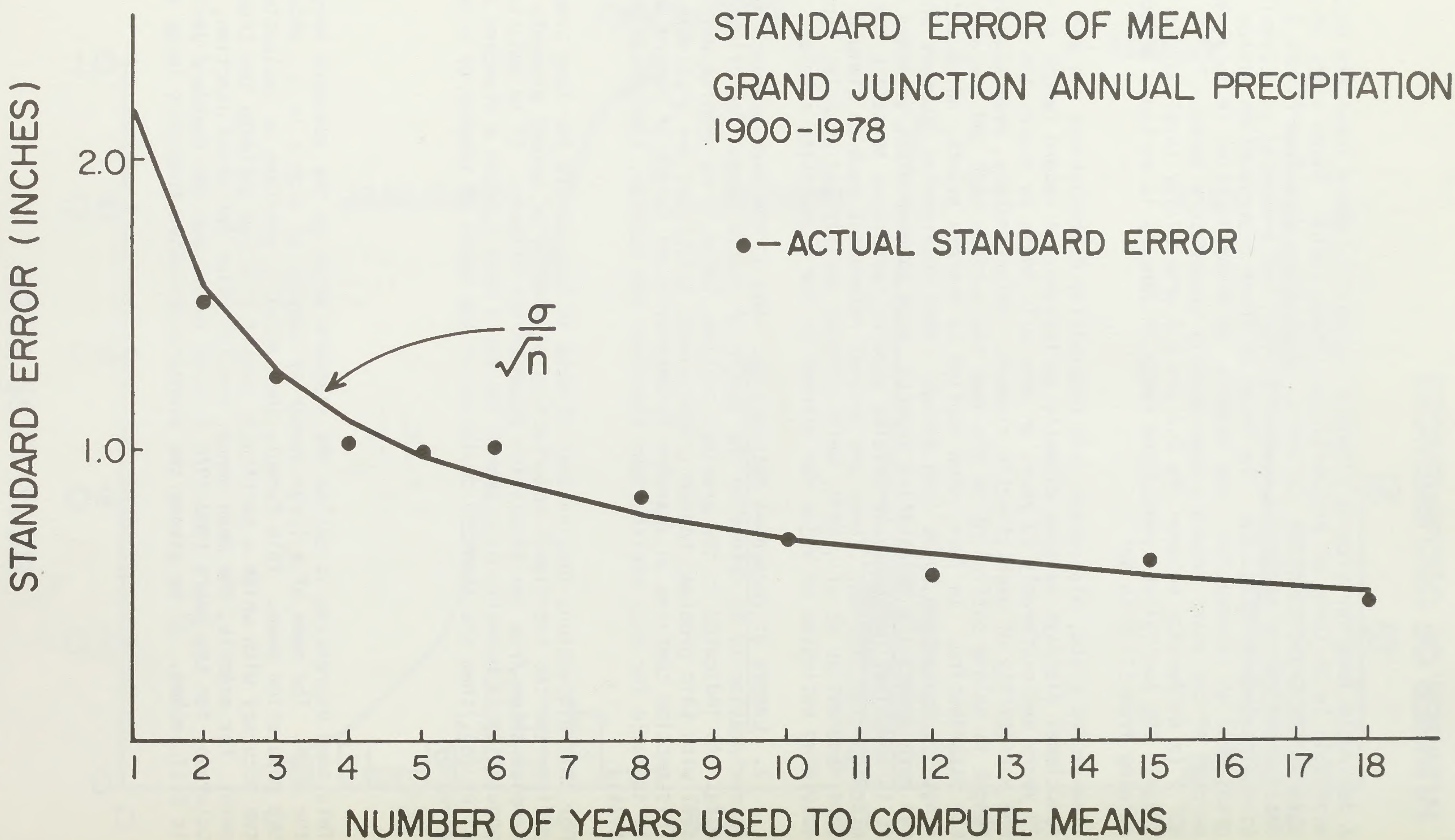
2. Length of Record--A Methodology. One of the ever-present problems in reclamation is to determine the length of record needed for climatic data. As indicated in the previous section, there is no precise way to deal with this problem; however, approximate guidelines are available. This section contains an approach to determine the length of record which is suitable for most applications (Snedecor and Cochran, 1967; Mood et al., 1974).

For this discussion, imagine that climate is very stable for long time periods and the individual observations of monthly or annual elements are samples taken from the population which is the climate. If in addition the population is normally distributed and has a mean (μ) and a standard deviation (σ), then the standard deviation of the means of samples of size n is given by

$$s = \frac{\sigma}{\sqrt{n}}$$

This same expression is called the standard error or the standard error of the mean. The mean of a large number of samples of size n is μ, which is the population mean. This formula then actually provides an indication of the accuracy with which a particular sample size can estimate the true mean. For example, the mean annual precipitation for Grand Junction, Colorado, for the years 1900-1978 is 8.46 inches and the standard deviation is 2.17 inches. If we assume the standard deviation from this large sample

Figure 6. Comparison of actual standard error (dots on graph) and theoretical standard error (solid line) as a function of record length. Annual precipitation data from Grand Junction, Colorado, 1900-1978.



of 79 years as the population standard deviation, then the standard error is $\sigma/\ n$ = 0.24 inches. Figure 6 shows the predicted and actual standard error of annual precipitation for Grand Junction as a function of the number of years in the sample.

If the means formed with n values are assumed to be normally distributed, a confidence interval for the mean can be determined. Approximately 68 percent of the means will fall within one standard error of the actual mean, and about 95 percent will fall within two standard errors of the actual mean. Thus, there is about one chance in three that the actual Grand Junction mean is not between 8.22 and 8.70 (8.46 $\pm$ 0.24) and one chance in twenty that the mean is not between 7.98 and 8.94 (8.46 $\pm$ 0.48).

The number of observations required to form a mean within a given tolerance can also be estimated. For the 95 percent confidence level the approximate expression is

$$n \approx \frac{4\,\sigma^2}{(\mathrm{tol})^2}$$

where tol is the desired tolerance. Thus, for the Grand Junction annual precipitation example, an estimate of the number of years of data required to form the mean within 0.5 inches is

$$n = \frac{4(2.17)^2}{(0.5)^2} = 75 \text{ years.}$$

In fact, many climatic elements are not normally distributed. However, most are not very different from normal. The estimates obtained using the expressions above are close enough to be useful in planning and carrying out climatic analyses for reclamation.

The previous sections have outlined the background and resources needed to develop a climate profile for an area. This section deals with the actual development of the profile and presents examples from the climate profile prepared for an area in north-central Colorado.

The Climate Profile

The climate profile is a tool which provides a structure and methodology for incorporating climatic information into the design, decisionmaking, and operational aspects of reclamation. The profile is intended to simplify, encourage, and quantify the use of climatic information in reclamation to increase efficiency, reduce losses, and enhance the probabilities of success. The ingredients in the profile are developed from the preceding sections.

Profile Development

The basic steps involved in developing a climate profile are to:

1) Identify reclamation activities.

2) Determine the responsiveness of activities to climate.

3) Identify the problems (and opportunities) from the responsiveness.

4) Prepare climatic analyses related to the problem (and opportunities).

5) Present the results of the climatic analyses in an easy-to-use format.

Each of the preceding sections has presented ideas and materials needed to develop the profile. The climate profile outline which combines the first four steps is given in Table 2 (p. 5), along with the associated climatic analyses.

A primary concern in discussing climate is that the vegetation to be used in reclamation must be suited to the climate. Table 2 has been developed to stress that the vegetation needs to be selected first so that later decisions can be made to enhance the probability of success based on the particular vegetation selected. The climatic data for Table 2 will usually be more available than the plant data.* Research is definitely needed to identify the climatic requirements for plants used in vegetation for reclamation.

*Definitions for each climate element in Table 2 are given in CPM.

Climate-sensitive reclamation activities have been identified in Section II and are shown in column 1 of Table 2. The impact of climate on each of the activities will vary from one geographic area to another as the climate varies. However, in each activity the impact of climate will lead to specific problems (or opportunities) or both. Once the problems have been identified, the next step is to prepare the climatic analyses appropriate to the problems.

Detailed long-term climate data, including daily temperatures, precipitation, snowfall and wind, should be used if possible in the development of a climate profile. Ideally, humidity, evaporation, solar radiation, and soil temperature information should also be available, but due to data limitations this is sometimes impossible. The only consistent source of such long-term, year-round data records is usually the NWS networks. Wind data are often not a part of available data sets.

Starting with NWS data available for a given area, preparation of climatic analyses can begin. Thereafter, as the special problems and data needs are determined, supplemental data sources can be located and included into the profile. It should be noted that many special climate summaries, studies, and reports have already been prepared by assorted public and private entities for many specific regions of the country, both large and small. These studies, which include environmental impact statements, resource studies, and national forest land-use plans, may have already assembled regional data from several sources in order to address particular land-use problems. Summarized climate information suitable for use in a climate profile may already be available and locating such studies can save many days of time and effort.

Another very real possibility is that no data truly representative of the area of interest or of sufficient length of record may be found. If such is the case, it may be necessary to immediately begin onsite data collection to document some of the characteristics of the local climate. When long-term data are sparse or nonexistent, the role of local residents familiar with the local climate in at least a qualitative way becomes much more important. Such expertise, although nonscientific, should not be overlooked.

The major concern in performing climatic analyses must be that the analyses present information that apply (directly or indirectly, quantitatively or qualitatively) to existing problems and/or opportunities. There is no benefit to be gained by spending time and money performing analyses which have no practical application. An example set of problems resulting from the impact of climate on reclamation activities is given in column 2 of Table 2. These may vary geographically and climatically, but a general set of problems emerge which affect mining and reclamation and which must be addressed by appropriate climatic analyses.

Four major problems appear in Table 2 which have impact in several activities. They include: (1) establishment and survival of plants, (2) water-caused erosion and pollution, (3) air-caused erosion and pollution, and (4) trafficability.

Each of these major problems reveals the interdisciplinary needs in reclamation. Climate is intimately involved in each problem and in the impact of each problem. However, climatic information alone is not sufficient to design reclamation programs or to make final decisions.

For example, climate provides the precipitation, temperature, wind, humidity, and radiation environment for the plants, but as indicated in Section II of Table 2, an ecosystem of complex interactions between air, soil, water, and plants combine to determine the probability of success for vegetation. A similar pattern emerges for water erosion and pollution. Heavy rainfall is the major causative factor, but the impact in terms of surface erosion and pollution of streams or lakes depends on many factors. The climate profile should contain the analyses which apply to each problem with the knowledge that other information is also needed to design and carry out an effective reclamation program.

As mentioned earlier, an example climate profile has been prepared for BLM for the McCallum study area in Colorado (McKee et al., 1981). The cold, semiarid location of the McCallum site dictates that the major concern is for survival of vegetation since the climate enforces many harsh restrictions. Climatic analyses were, therefore, designed to address those particular aspects of climate most likely to limit plant establishment.

CLIMATIC INFORMATION, PRESENTATION AND INTERPRETATION

The climatic analyses included in the profile will be used primarily by individuals that do not have specialized training in climatology. Consequently, the method of information presentation is important if the information is to be effectively and widely used.

Three separate aspects of climate, included in the climate profile, are: (1) average conditions, (2) variability, and (3) extreme events. Each is an important feature of climate for reclamation and needs to be identified. These apply to separate climatic elements as well as the overall climate system which combines all climatic elements.

(1) Average conditions are usually easy to display and understand. They allow comparison with other geographical locations and give a good idea of what to expect, seasonally and annually, over a number of years. Average information is often readily available.

(2) Variability of climate is somewhat harder to display and explain. Variability is usually shown in a probability form and is the type of information most useful to much of the planning process. Information on climatic variability is usually not available in standard summary references and will have to be developed for most reclamation sites.

(3) Extreme events such as unusually hot or cold temperatures, drought, heavy rain, and high winds are important and can generally be presented in simple and understandable forms. However, for extreme events it becomes very important that sufficiently long-term data are available and used.

New methods of information presentation are needed to allow non-climatologists to make the best use of climatic information. Tables, graphs, and maps have been used extensively in information presentation. Users seem to prefer graphical data presentations which have been prepared to answer specific questions. The key should be to present information so that it is easily used with a minimum of effort.

The development of the climate profile should include analyses which address the important problems for the area in question. These will vary as a function of climate, geographic location, and other factors. As a result, different analyses should be considered depending on the problems and opport nities most likely to be encountered at a particular site.

CLIMATIC ANALYSES*

Effective use of climatic information in reclamation must include a data base which is accurate and accessible and which has a capability to process the data into useful information.

The Colorado Climate Center is developing an accessible and functional climatic data base for Colorado and Montana (Wyoming, Utah, North Dakota, New Mexico, Oklahoma, and Alabama also will be developed in the near future) based on daily and monthly data from the climatic observation stations in Colorado and Montana. The climate information system will include a data base, analysis programs to process data into information, a display capability in graphics and tables, and a users' guide to allow efficient use of the system.

Climate Data Bases

As mentioned earlier in this report, the primary climatic data in the United States are collected by the National Weather Service and archived by the National Climatic Center on a daily and monthly basis. The historic data, including stations no longer active, amount to two or three times the number of current stations. These data are archived at NCC as separate data sets for daily and monthly data. The same separation will be maintained in the data bases. The data will be obtained on magnetic tape and transferred to a storage disc which will be used on the CDC Cyber Computing System of the Bureau of Reclamation facility at the Denver Federal Center.

The data as received from NCC have a variety of problems, which include variable record lengths and erroneous and missing data. Data will be "cleaned" back to 1951 for routine errors and errors which cause the daily data to be inconsistent with the monthly data. Recording procedures at NCC are responsible for variable record lengths of daily and monthly data for the same station. Daily data that have been used for calculating monthly data have been published in hard copy but not included on the daily magnetic tapes. This data will be keypunched and added to the daily data set back to 1951. An index of stations and an inventory of all data in the data base will also be prepared.

Analysis Programs

A set of computer programs which are compatible with the CDC Cyper Computer will be available to access and operate on data from the state data bases.

*This section was written by the Division of Special Studies' climatologist, Elwyn L. Rolofson, and was not a part of the original report from Colorado State University.

The programs will be designed to specify climate data that can be useful for applications in reclamation. Each of the programs has been used in previous climate profiles analyses (see Table 4).

Graphic display routines will be developed for each of the analyses programs. The routines will route the data to devices that will enable the user to display or plot information in graphical form. The devices to be used initially are the Hewlett-Packard Model 85, a Tektronics Graphic Terminal, and a XYnetics flat-bed plotter. The routines will be compatible with the DISSPLA graphics software system.

Users' Handbook

A users' handbook will be made available which will include a description of the data base, step-by-step instructions on the use of all analyses programs, and a description of what each analysis program produces. The handbook will allow users with limited experience with computers to access data and obtain desired analyses in hard copy tables or graphs.

Table 4. Climatic Analyses.

1. Spring and fall freeze data statistics and freeze-free periods.
2. Monthly average maximum, minimum and mean temperatures and daily extremes.
3. Average number of days with: minimum $\leq$ 32° F, maximum $\leq$ 32° F and minimum $\leq$ 0° F.
4. Average daily maximum, minimum and mean temperatures and daily extremes.
5. Average number of days per month with precipitation: $\geq$ 0.10 in., $\geq$ 0.20 in., $\geq$ 0.50 in.
6. Average monthly precipitation.
7. Average number of days with > 1 in. snow on the ground.
8. Average monthly snowfall.
9. Thermal growing season.
10. Probability of n-day period with mean temperature greater than threshold.
11. Display data above or below threshold.
12. Probability of daily minimum temperature dropping to < 0° F, < -10° F, < -20° F, < -30° F, < -40° F.
13. Probability of daily maximum temperature exceeding > 75° F, > 80° F, > 85° F.
14. Probability of receiving X inches or less precipitation for winter, summer, and annual.
15. Probability that a year has n day or less of precipitation equal to or greater than X inches.
16. Same as 15 except snowfall (one day).
17. Same as 15 except snowfall (storm).
18. Probability of having snowdepth on ground exceeding threshold.
19. Joint probability of receiving precipitation and being within thermal growing season.
20. Monthly potential evapotranspiration (Blaney and Criddle Method).
21. Period-of-record summary.
22. Growing degree days.

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